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Brett Allen
U.S. Department of Agriculture

Andrew W. Lenssen
Iowa State University, alenssen@iastate.edu

Upendra M. Sainju
U.S. Department of Agriculture

Jalal D. Jabro
U.S. Department of Agriculture

William Stevens
U.S. Department of Agriculture

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Nitrogen use in spring wheat impacted by crop diversification, management, and tillage

Abstract

Dryland wheat production potential in the northern Great Plains (NGP) often is limited by N availability impacted by various management practices. A 4-yr study was conducted in northeast Montana to relate spring wheat (*Triticum aestivum* L.) productivity and N utilization to management system (conventional and ecological), tillage (till and no-till), and four crop rotations (continuous spring wheat, spring wheat-pea [*Pisum sativum* L.], spring wheat-hay barley [*Hordeum vulgare* L.]-pea, and spring wheat-hay barley-corn [*Zea mays* L.]-pea. Ecological management included greater seed rates, delayed planting dates, banded N fertilizer, and increased stubble height compared to conventional management with standard seed rates and planting dates, short stubble height, and broadcast N fertilizer. Continuous spring wheat showed the lowest grain yield, with the least efficient utilization of N compared to 2, 3, and 4-yr rotations. Mineral nitrogen-use efficiency (NUE) was 37% lower for continuous wheat than other rotations. Increasing complexity of crop rotation had little impact on wheat production or N relationships. The delayed planting date associated with ecological management of spring wheat contributed to 33% less efficient use of N compared to an early planting date with conventional management. Overall, results indicated that crop rotation and management system often impacted N relationships with wheat production, while tillage impacts differed with year. Differences in yield and N use of spring wheat varied among years, underscoring the need to refine management systems given the highly variable precipitation patterns typical of the NGP.

Keywords

nitrogen harvest index, nitrogen productivity, nitrogen recovery index, nitrogen use, nitrogen use efficiency

Disciplines

Agriculture | Agronomy and Crop Sciences | Soil Science

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Nitrogen Use in Spring Wheat Impacted by Crop Diversification, Management, and Tillage

B.L. Allen[1], A.W. Lenssen[2], U.M. Sainju[1], J.D. Jabro[1], and W.B. Stevens[1]

[1]USDA-ARS, Sidney, MT; [2]Iowa State Univ., Ames, IA

ABSTRACT

Dryland wheat production potential in the northern Great Plains (NGP) often is limited by N availability impacted by various management practices. A 4-yr study was conducted in northeast Montana to relate spring wheat (*Triticum aestivum* L.) productivity and N utilization to management system (conventional and ecological), tillage (till and no-till), and four crop rotations (continuous spring wheat, spring wheat-pea [*Pisum sativum* L.], spring wheat-hay barley [*Hordeum vulgare* L.]-pea, and spring wheat-hay barley-corn [*Zea mays* L.]-pea. Ecological management included greater seed rates, delayed planting dates, banded N fertilizer, and increased stubble height compared to conventional management with standard seed rates and planting dates, short stubble height, and broadcast N fertilizer. Continuous spring wheat showed the lowest grain yield, with the least efficient utilization of N compared to 2, 3, and 4-yr rotations. Mineral nitrogen-use efficiency (NUE) was 37% lower for continuous wheat than other rotations. Increasing complexity of crop rotation had little impact on wheat production or N relationships. The delayed planting date associated with ecological management of spring wheat contributed to 33% less efficient use of N compared to an

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Keywords: nitrogen harvest index; nitrogen productivity; nitrogen recovery index; nitrogen use; nitrogen use efficiency

Abbreviations: NGP, northern Great Plains; NHI, nitrogen harvest index; NRI, nitrogen recovery index; NUE, nitrogen use efficiency; MUN, mineral used nitrogen.

Soil water and N availability are the two primary factors limiting crop productivity in semi-arid dryland cropping systems (O'Leary and Conner, 1997; Padbury et al., 2002). In the North America northern Great Plains (NGP) the traditional cropping system is spring wheat (SW)-fallow where the fallow system helps to mineralize plant nutrients and accrue soil water to increase crop yield in the subsequent year (Haas et al., 1974; Allen et al., 2011a). However, precipitation storage efficiency during the fallow period is usually limited to about 15 to 40% of rainfall due to water losses from soil surface evaporation, transpiration by weeds, and sometimes by surface runoff and deep drainage (Black and Power, 1965; Peterson et al., 1996). The practice of summer fallow can lead to detrimental impacts on soil quality, including increased wind- and water-induced erosion, development of saline seeps, and decreased C and N pools in mineral and organic pools (Black et al., 1981; Sainju et al., 2015). Annualized crop yields and total economic returns typically are greater

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with continuous cropped systems than a crop-fallow rotation (Aase and Schafer, 1996; Sainju et al., 2015). As a result, summer fallow area has decreased in the NGP. For example, wheat following fallow acreage in Montana decreased by 19% from 1999 to 2008 (NASS, 2009). During the same time period, alternative cropping systems increased in the NGP where, for instance, pulse and oilseed crops increased from <75,000 ha in 1990 to >710,000 ha in 2010 in 25 counties in northeast Montana and northwest North Dakota (Hansen et al., 2012).

Crop rotation affects soil N availability to subsequent crops. More information is needed regarding the impact of pulses, annual forages, and dryland corn on N use in wheat cropping systems common in the NGP. Long-term research in the NGP showed that lentil (*Lens culinaris* Medik. cv. Indianhead) harvested early for green manure in place of fallow increased N cycling and preplant soil nitrate for a subsequent SW crop (Pikul et al., 1997; Allen et al., 2011b). In contrast, Lenssen et al. (2007b) reported decreased seed N, biomass N, N harvest index, and NUE in SW following lentil, pea, and chickpea than SW following fallow in MT during drought conditions. Entz et al. (2002) noted the potential of annual forages to improve N retention in dryland cropping systems.

Tillage is a traditional management practice used to control weeds, incorporate crop residues into soil, and prepare seedbeds prior to planting. However, tillage is also linked to numerous detrimental impacts such as loss of soil organic matter, reduced soil water holding capacity, and increased soil erosion (Aase and Pikul, 1995; Cihacek and Ulmer, 2002; Gao et al., 2016) leading to a rapid increase of no-till land area in the NGP. For instance, in the MonDak (NE Montana and NW North Dakota) region, no-till land area increased ten-old from 58,560 ha in 1989 to 580,600 ha in 2002 (Hansen et al., 2012). More recent estimates from the 2017 U.S. Census of Agriculture indicated no-till acres in Montana from 2012 to 2017 increased from 2.8 to 3.3 million ha.

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Other management practices shown to improve SW production include increased crop stubble height (McMaster et al., 2000), banded fertilizer placement (Jacobsen et al., 1993), and earlier seeding date and increased seed rate (Forster et al., 2017).

Recent efforts have identified potentials and limitations of NUE in wheat (Prey, et al. 2019), however there is limited knowledge on the impact of crop diversification, tillage, and other management practices on N use relationships in dryland SW. Inefficient use of N inputs results in N loss due to surface runoff, leaching, denitrification, volatilization, and nitrous oxide emissions. Producers can likely improve NUE in SW by changing from monocultures to more diversified crop rotations that include pulse, annual forage, and warm-season grass crops (Lenssen et al., 2007a; 2007b). We hypothesized that no-till SW under ecological management in diversified cropping systems with pea, barley forage, and corn would increase NUE compared to a tilled continuous SW rotation under conventional management. The objective of this study was to investigate crop yield with soil and plant N relationships in SW as impacted by tillage, management level, and cropping system diversity for the final four years (2009-2012) of a long-term experiment that began in 2004. For the purposes of this paper, 2004-2008 were considered the establishment phase to complete a full cycle of the 4-yr rotations.

MATERIALS AND METHODS

A long-term experiment was conducted from 2004-2012 at a USDA-ARS experimental site (47°46'N; 104°16'W; 690 m elevation), located 8 km northwest of Sidney, MT. Previous reports from the study included yield and simulated water availability in continuous SW from 2004 to 2010 (Qi et al., 2013), yield and water use of wheat (Lenssen et al., 2014), barley hay (Lenssen et al., 2015), and corn (Lenssen et al., 2017) from 2005-2010, soil total C and N and crop yield (Sainju et al, 2017), and

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N balance (Sainju et al., 2018) across rotations from 2004 to 2011. The 30 yr average annual precipitation is 363 mm, with about 76% occurring in the growing season between April and September (Table 1). The soil at the field site was mapped as Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls) with 1-2% slope. Soil samples taken to a depth of 15 cm had an average pH of 6.1, organic C of 18 g kg^{-1}, and Olsen P of 12 mg kg^{-1}, as reported by Lenssen et al., 2014. The previous 30-yr cropping history was a SW-summer fallow rotation, with tillage performed three to five times per fallow period to control weeds.

The treatments included four SW-based crop rotations (1, 2, 3, and 4-yr) and two management systems in a split-plot arrangement. The whole plot factor was tillage (till and no-till) system and the split plot factor was a factorial combination of two management systems (conventional and ecological) and four crop rotations. Each treatment was replicated three times in a randomized complete block design, with each phase of crop rotations present each year, for a total of 120 plots. The plot size measured 12.2 m in length by 12.2 m in width.

Rotations were continuous SW, SW-pea, SW-barley hay-pea, SW-barley hay-corn-pea as described in Table 1 of Sainju et al., 2017. Management systems were conventional (standard seeding rate, stubble height, planting date, and broadcast N fertilization) and ecological (increased seeding rate and stubble height, delayed planting date to allow initial flush of weeds to emerge, and banded N fertilization). Seeding dates, rates, and plot management were described by Lenssen et al. (2014) and are summarized in Table 2. Tillage systems were no-till and tillage to a depth of 7-8 cm in the spring with a single pass field cultivator with 45 cm-wide sweeps and coil-tooth spring harrows.

Fertilizer N rate for SW (based on a yield goal of 2350 kg ha^{-1} with 14% grain protein) was 118 kg N ha^{-1} applied from urea (46% N), which was adjusted by subtracting N from monoammonium phosphate fertilizer and for residual soil NO_3-N (0-60 cm depth; kg N ha^{-1}) that was determined from

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soil samples taken in the previous fall (Jacobsen et al., 2005). A credit of 11.2 kg N ha^{-1} was given to wheat that followed pea. Urea was broadcast just prior to planting on conventionally managed plots and banded 5 cm below and 5 cm to the side of seed at planting on ecologically managed plots. Also banded to all plots at planting were 56 and 45 kg ha^{-1} monoammonium phosphate, and potassium chloride, respectively.

Spring wheat ‘Reeder’, dry pea ‘Majoret’, and barley ‘Haybet’ from all treatments were planted on 20.3 cm row spacing with a custom built drill with double shoot Barton single disk openers for single pass seeding and fertilizer application. Pioneer ‘39D95’ RR2 Poncho 250 treated-corn seed (78 RM hybrid) was planted with a John Deere MaxEmerge Plus planter (John Deere and Co., Moline, IL) with 61.0 cm row spacing.

Aboveground biomass from two 0.5-m^2 areas in wheat plots was collected a day or two before combine harvest, dried at 55^{o}C for 7 d, and weighed. Grain yield was measured with a plot combine (Kincaid 8-XP, Haven, KS). Yield samples were dried at 55^{o}C, cleaned with forced air and sieves, and weighed. Subsamples of biomass and grain were ground to pass a 1-mm sieve in rotary and cyclone mills, respectively, and analyzed for N with a LECO FP-2000 C-N analyzer (LECO Corp., St Joseph, MI). Biomass and grain data were adjusted to 100% dry matter.

Soil samples (3.2-cm diameter core) were taken each spring and fall to a depth of 120 cm in 15 cm increments for the surface 30 cm and in 30 cm increments thereafter. Soil was dried at 25°C, sieved to 2 mm, extracted with 2M KCl, and analyzed for NO_3-N and NH_4-N concentrations (Mulvaney, 1996) by flow injection with a LACHAT QuickChem 8000 analyzer (Hach Company, Loveland, CO). Soil bulk density from samples taken in fall 2010 averaged 1.36, 1.37, 1.39, 1.55, and 1.60 Mg m^{-3} for the 0-15, 15-30, 30-60, 60-90, and 90-120 cm sampling depths, respectively. Bulk

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density values were used to convert NO_3-N and NH_4-N concentrations (g N kg^{-1}) to contents (kg N ha^{-1}) at a particular depth by multiplying concentrations by bulk density and thickness of the soil layer.

Nitrogen use efficiency indicators included mineral used nitrogen (MUN), NUE for biomass, NUE for grain, nitrogen harvest index (NHI), and nitrogen recovery index (NRI). The MUN is calculated as available N at planting (spring soil NO_3-N to a 60 cm depth plus applied fertilizer) minus fall soil NO_3-N to a 60 cm depth, with the assumption that N loss to the environment was negligible based on weather data. The NUE for biomass is measured by dividing aboveground biomass yield by MUN. The NUE for grain is grain yield divided by MUN. The NHI is the proportion of grain N in total aboveground biomass N, and the NRI is the proportion of grain N relative to total N inputs (fertilizer N and preplant nitrate to a 60 cm depth).

Statistical Analysis

Data were analyzed using PROC GLIMMIX model (SAS 9.1, 2003) with appropriate error terms for a split-plot design (Littell et al., 1996). Tillage, management, crop rotation, and year were considered fixed effects and replication a random effect. Tillage was considered as the main plot and the combination of crop rotation x management (conventional vs. ecological) was the split plot. Mean separation tests were conducted using Tukey's honest significant difference. The NUE of grain and NUE of biomass data were normalized prior to analysis using a Log_{10} transformation, but non-transformed means are presented in the paper for reader convenience. Treatment differences are reported at the 5% level of significance.

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RESULTS AND DISCUSSION

Weather

Air temperature and precipitation for 2009-2010, previously reported by Lenssen et al. (2014), in addition to that for 2011-2012 are shown in Table 1. Monthly average growing season (April to September) air temperature ranged from 5°C below normal in April 2011 to 2°C above normal in July 2012. Overall monthly air temperature during the 2009-2012 growing seasons was 1.8°C below the 30-yr mean, where only 2 of 24 months during that period exceeded the 30-yr mean temperature. Growing season precipitation (April to August) ranged from 177 mm (2012) to 369 mm (2010), which represents 64% and 134% of the 30-yr mean (275 mm). In general, air temperature during the 2009 growing season was generally cooler than the 30-yr mean, with the exception of a warmer than normal period in Sep. Growing season precipitation during 2009 was 81% of the 30-yr mean, marked by unusually dry periods in May, Jun, and Sep, and relatively wet periods during Apr and Aug. The 2010 cropping season was cool and notably wet (142 mm precipitation in May alone) compared to the 30-yr mean. The 2011 cropping season was also cooler and wetter than normal, especially during May (146 mm precipitation) with relatively dry periods during Jun and Aug, and to a lesser degree, in Sep. The 2012 growing season was the warmest (though overall still 0.5°C less than the 30-yr mean) and driest of the study period, where precipitation during Apr-May was slightly above the mean followed by drier than normal periods, especially during Jun, Jul and Sep.

Spring Wheat Biomass and Grain Yield

Spring wheat biomass and grain yields for 2009-2010 were reported by Lenssen et al. (2014) and are included in Table 3 for the reader's convenience. Crop biomass from 2009-2012 ranged from 4628 to 7394 kg ha^{-1} and differed (P<0.05) for rotation, management system, and year, but not for tillage system. Several interactions for crop biomass were significant (Table 3), including those for

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rotation × year (Table 4), management × year (Table 5), and tillage × year (Table 6). Crop biomass was similar among rotations for all years except in 2010 where wheat biomass in 2- and 3-yr rotations was about 20% greater than that for continuous wheat (Table 4). Crop biomass was similar between management systems in 2009 and 2011, but was 18% and 41% greater for conventional than ecological wheat in 2010 and 2012, respectively (Table 5). Crop biomass was similar between tillage systems in all years except in 2010 where tillage increased biomass by 9% compared to no-till (Table 6).

Spring wheat grain yield from 2009-2012 ranged from 2107 to 2703 kg ha^{-1} and differed (P<0.05) for rotation, management system, and year, but not for tillage system. Other NGP dryland research has reported soil, environmental, and economic benefits of no-till (compared to tillage) without reducing crop yields (Aase and Schafer, 1996; Lenssen et al., 2007a; Sainju et al., 2009). Grain yields in the 2-, 3-, and 4-yr rotations were about 10% greater than those for continuous wheat (Table 3), showing the production advantage of crop rotation in wheat (Miller et al., 2002; Gan et al., 2003; Tanaka et al., 2007). Lenssen et al., 2014 attributed increased production in diversified rotations compared to continuous wheat to greater available soil water, N, and/or weed control. For example, pea uses less water than spring wheat and also supplies N from its residue because of its low C/N ratio or high N concentration (Lenssen et al., 2007a; Lenssen et al., 2007b). The interaction was significant (P<0.05) for management × tillage × year (Table 7), where grain yield was similar in 2009 regardless of management or tillage. In other years, the most noticeable differences were between management systems, where conventional wheat grain yields were typically greater than those for ecological wheat and the impact of tillage was less consistent. The greater grain yield in conventional wheat in 2010, 2011, and 2012 was likely related to the earlier (three week) planting date than ecological wheat. Delayed planting can lead to increased plant stress during periods of

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high heat and drought (Reynolds et al., 2007; Lenssen et al., 2014), such as that during grain fill in 2012.

Soil N for Spring Wheat

Pre-plant soil NO_3-N (0-60 cm depth) from 2009-2012 ranged from 29 to 65 kg ha^{-1} and differed (P<0.05) for rotation and year, but was similar for management and tillage systems (Table 3). The interaction was significant (P<0.05) for rotation × tillage × year. Pre-plant soil NO_3-N was similar regardless of rotation or tillage in all years except in 2009 where NO_3-N content for tilled continuous wheat was about 2 to 5 times greater than that for all other combinations of tillage and rotation (Table 8). The greater pre-plant soil NO_3-N in 2009 tilled continuous wheat was likely related to increased short-term N mineralization from tillage (Kristensen et al., 2003) and residual N from the 2008 cropping year where continuous wheat (versus other rotations) and no-till management (versus tilled management) had considerably lower biomass and grain yield during the drought year that received only 53% of normal precipitation (Lenssen et al., 2014).

Post-harvest soil NO_3-N (0-60 cm depth) from 2009-2012 ranged from 17 to 44 kg ha^{-1} and differed (P<0.05) for rotation and year, but was similar for management system and tillage system (Table 3). The interaction was significant (P<0.05) for rotation × year (Table 4). Post-harvest soil NO_3-N was similar for 2010 and 2011, but was about twice under continuous wheat than other rotations in 2009 and under the 3-yr rotation in 2012. The greater post-harvest soil NO_3-N in continuous wheat than other rotations was likely related to the less efficient use of N in continuous monocropped systems in the BNGP (Miller et al., 2003) and in 2009 from the relatively greater available N in the surface 60 cm.

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Spring Wheat Biomass and Grain N

Biomass N concentration from 2009-2012 ranged from 14.0 to 19.1 g kg^{-1} and differed (P<0.05) for rotation, management system, and year (Table 3). The interaction was significant (P<0.05) for rotation × management × tillage, management × year and tillage × year (Table 3). Biomass N concentration was generally lower in no-till conventional management of wheat in 2-, 3-, and 4-yr rotations (Table 9). This can be explained in part as wheat was more efficient at allocating N resources to grain in tilled wheat under ecological management compared to no-till conventional management (Table 3). Biomass N concentration was similar among years for rotation, except for 2010 and 2012 where the N concentration for ecological management was 15% and 19% greater, respectively, than for conventional management (Table 5). The delayed planting date with ecological treatment in 2010 and 2012 likely contributed to reduced plant growth and relatively high biomass N concentrations during the drought conditions and/or heat stress (Lenssen et al., 2014). Biomass N concentration was similar among years for tillage, except for 2009 and 2010 where that for the tilled treatment was 11% and 15% greater, respectively, than that for the no-till treatment (Table 6). Tillage likely contributed to a short-term increase in available N from the mineralization of soil organic matter (Kristensen et al., 2003).

Biomass N yield from 2009-2012 ranged from 79 to 111 kg ha^{-1} and differed (P<0.05) by year (Table 3). The interaction was significant (P<0.05) for rotation × year, management × year, and tillage × year. Biomass N yield was similar among years for rotation, except for 2010 where N yield for wheat in the 2-yr rotation was 26% greater than that for continuous wheat (Table 4). The lower biomass N yield in continuous wheat than the 2-yr rotation was likely a result of the relatively lower N concentration and especially the lower biomass yield often associated with wheat monocultures (Gan et al., 2003). Biomass N yield was similar among years for management, except for 2011 and

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2012 where N yield for conventional management was 16% and 15% greater, respectively, than that for ecological management (Table 5). Reduced biomass N yield in wheat under ecological management was likely related to the delayed planting date, especially for 2011 when excessive rainfall delayed planting till Jun 9, that significantly reduced biomass production compared to conventional management (Table 3). Biomass N yield was similar among years for tillage, except for 2010 where N yield for tilled wheat was 26% greater than that for no-till wheat (Table 6). The greater biomass N in 2010 wheat under tillage was a product of significantly greater biomass production and biomass N concentration than no-till wheat (Table 6). Above average precipitation during the 2010 growing season (Table 1) in addition to greater N mineralization associated with tillage (Kristensen et al., 2003) likely contributed to the relatively greater biomass N yield in tillage than no-till wheat in that year.

Grain N concentration from 2009-2012 ranged from 22.6 to 28.9 g kg^{-1} and differed (P<0.05) for rotation, management system, tillage system, and year (Table 3). The interaction was significant (P<0.05) for rotation × management, rotation × year, management × year, and tillage × year. Grain N concentration was similar among rotations and management except for the 3-yr rotation under conventional management that was 9% to 17% lower than other rotation and management combinations (Table 10), for which we have no supported explanation. Grain N concentration was similar among years for rotation, except for 2009 where the N concentration for continuous wheat was about 19% greater than for wheat in 2- and 3-yr rotations, with wheat in the 4-yr rotation being intermediate (Table 4). In spite of greater grain N uptake, monoculture wheat grain yields were significantly reduced compared to wheat in diverse rotations, supporting reports of increased yield with crop rotation (Farahani et al., 1998; Gan et al., 2003; Tanaka et al., 2007; Lenssen et al., 2014; Schlegel et al., 2017). Grain N concentration was about 13% greater in ecological than conventional management for 2010 and 2012, but was 13% greater in conventional than ecological management

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in 2011 (Table 5). The greater grain N concentration in ecological than conventional wheat in 2010 and 2012 was likely due in part to fertilizer placement (banded below the soil surface versus surface broadcast) and the delayed planting date accompanied with late season drought conditions (Table 1) that led to relatively lower wheat biomass production (Table 5) with high N concentration in biomass and grain (Table 5). Similarly, in the NGP Jacobsen et al. (1993) noted that banded N fertilizer increased biomass N concentration and content. Forster et al. (2017) reported that delayed planting date of dryland durum wheat decreased yield. The decreased grain N concentration in 2011 ecological than conventional wheat was probably related to the very late planting date of ecological wheat on June 9 as a result of an unusually wet spring that reduced plant growth via an abbreviated growing season. Grain N concentration was similar among years for tillage, except for 2010 where the N concentration for tilled wheat was 14% greater than that for no-till wheat (Table 6), possibly a result of increased N availability associated with tillage (Kristensen et al., 2003).

Grain N yield from 2009-2012 ranged from 53 to 78 kg ha^{-1} and differed (P<0.05) for management system and year, but was similar for rotation and tillage system (Table 3). The interaction was significant (P<0.05) for rotation × year, management × year, and tillage × year. Grain N yield was 20% greater in the 2-yr than the 4-yr rotation in 2010 and 24% greater in the 4-yr rotation than continuous wheat in 2012 (Table 4), largely a result of the relatively greater grain yield, as grain N concentration was similar between the rotations. Grain N yield was 15 to 30% greater in conventional than ecological management in 2011 and 2012 (Table 5), likely attributable to the previously described very delayed planting date of ecological wheat in 2011 and the delayed planting in conjunction with late season drought in ecological wheat in 2012. Grain N yield was 17% greater for tilled than no-till wheat in 2010 (Table 6), possibly related to short-term increased availability of N from mineralization associated with tillage (Kristensen et al., 2003) and greater yield potential of tilled wheat in wet years (Neugschwandtner et al., 2015).

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Spring Wheat N Use Efficiency

The NHI from 2009-2012 ranged from 0.59 to 0.71 and differed (*P*<0.05) for management system and year, but was not significant for rotation and tillage systems (Table 3). The NHI was 10% greater in conventional than ecological management, likely due to the 3-wk delayed planting date in ecological wheat leading to reduced grain yield and inefficient partitioning of N to grain. The NHI was also notably greater for 2009 and 2011 than 2010 and 2012. Lower than normal rainfall during grain fill in July in 2010 and 2012 (Table 1) likely decreased grain N uptake. Higher than normal temperatures in July 2012 also likely contributed to lower NHI, as Lenssen et al. (2014) suggested heat stress during grain fill can lead to inefficient partitioning of N to grain.

The NRI from 2009-2012 ranged from 0.7 to 1.2 and differed (*P*<0.05) for rotation and year (Table 3). The interaction was significant (*P*<0.05) for rotation × year and tillage × year. The NRI was similar among years for rotation, except for 2009 where NRI was 55% less for continuous wheat than other rotations and in 2012 where NRI was 38% less in continuous wheat than the 2-yr rotation (Table 4). Gan et al. (2003) also suggested more efficient use of N in spring wheat rotations with pea compared to monoculture wheat. The NRI was greater in the no-till than the tilled system in 2009 (Table 6), likely related to increased efficiency of N uptake in no-till systems during periods of drought in May and June 2009. Lenssen et al. (2007b) reported greater NRI in one of four years for no-till compared to tilled wheat where greater water storage in no-till likely extended the period of N uptake compared to drier tilled soil conditions.

The MUN from 2009-2012 ranged from 44 to 81 kg ha^{-1} and differed (*P*<0.05) for rotation and year, with significant (*P*<0.05) interactions for rotation × year and tillage × year (Table 3). The MUN was twice that for continuous wheat than other rotations in 2009 but not differ among crop rotations in other years (Table 4). The greater MUN in continuous wheat was likely influenced by the

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severe drought in 2008 that led to reduced water use and yield compared to other rotations (Lenssen et al., 2014) and increased preplant soil nitrate previously described for 2009 (Table 8). The MUN was 68% greater for tilled than the no-tilled system in 2009 (Table 6), possibly related to increased N availability associated with tillage (Kristensen et al., 2003).

The NUE for aboveground biomass from 2009-2012 ranged from 141 to 363 kg biomass kg^{-1} N and differed (P<0.05) for rotation and year, with a significant tillage × year interaction (Table 3). The NUE was 55 to 70% greater in 2- and 3-yr rotations than for continuous wheat. Intermediate NUE in the 4-yr rotation could be related to the diminishing impact of pea being included one in four years. The NUE was 63% greater in the no-till than the tilled system in 2009, a result of the relatively greater impact of biomass than MUN in no-till wheat that year (Table 6). The previously discussed drought in 2008 (Lenssen et al., 2014) and a dry May and June in 2009 likely contributed to the greater N efficiency in no-till than tilled wheat.

The NUE for grain from 2009-2012 ranged from 48 to 146 kg grain kg^{-1} N and differed (P<0.05) for rotation, management system, and year, with a significant tillage × year interaction (Table 3). The NUE for grain was 62 to 75% greater in 2- and 3-yr rotations than continuous wheat supporting reports of increased NUE in diversified cropping systems that include legumes compared to wheat monocultures (Karlen et al., 1994; Huggins and Pan, 2003). The 4-yr rotation also included a leguminous crop, but perhaps the rotational N benefit diminished when pea was only present one in four years. Conventional management showed a 49% greater NUE for grain than ecological management, in part due to the 3-wk delayed planting date in ecological wheat that likely limited N uptake in the current study and yield and water use efficiency reported by Lenssen et al. (2014). The NUE for grain was 68% greater in the no-till than the tilled system for 2009 (Table 6), likely for similar reasons described previously for NUE in biomass.

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CONCLUSIONS

Rotation intensity, management system, and tillage system each played a key role in the development of sustainable dryland spring wheat cropping systems under the environment that occurred for the Sidney, MT experimental site. Our study showed that wheat grain production practices affected N utilization under the study site environment from 2009-2012. Crop rotation and management system often impacted N relationships with wheat production, while tillage impacts differed among years. Continuously cropped spring wheat showed the least favorable N relationships, though neither the three or four year rotations offered greater N benefits compared to the two year rotation. Ecological management of spring wheat generally used N less efficiently than that under conventional management, likely due in part to the delayed planting date of the ecological management practice. Differences in yield and N use of spring wheat varied significantly among years, emphasizing the need to develop management tools that optimize cropping system N uptake despite the typical highly variable precipitation patterns of the NGP.

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Table 1. Precipitation and air temperature at the research site near Sidney, MT, 2009-2012.

	Precipitation					Temperature				
	2009	2010	2011	2012	30-yr†	2009	2010	2011	2012	30-yr†
	mm					°C				
April	39	29	39	33	27	5	8	4	8	9
May	8	142	146	58	52	12	10	10	12	14
June	56	71	24	26	71	16	17	17	18	19
July	70	51	68	38	64	19	20	22	24	22
August	38	56	15	21	29	19	20	21	21	22
September	13	20	20	2	32	18	13	16	16	16
Season total	224	369	312	177	275					
Yearly total	282	415	347	233	364					

† 30-yr mean (1981-2010) from Western Regional Climate Center for Sidney, MT, located 8 km southeast of the research site.

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Table 2. Seeding rate, N fertilizer placement, P and K fertilizer placement, planting date, and stubble height of

crops grown in conventional or ecological management near Sidney, MT, 2009-2012.

Crop	Management	Seeding rate	N placement	PK placement	Planting date	Stubble height
		thousand seeds ha^{-1}				cm
Spring wheat	conventional	2224	broadcast	banded	early April	20
	ecological	2965	banded	banded	early May	30
Pea	conventional	700	banded	banded	early April	5
	ecological	969	banded	banded	early April	5
Forage barley	conventional	2224	broadcast	banded	early April	5
	ecological	2965	banded	banded	early April	5
Corn	conventional	25†	broadcast	none	early May	20
	ecological	25	banded	none	early May	20

† seeding rate for 2009 ecological corn was 37,000 seeds ha^{-1}.

Table 3. Treatment means and analysis of variance for crop biomass, grain yield, pre-plant soil nitrate N ($PreNO_3$), post-harvest residual soil

nitrate N ($PostNO_3$), biomass N, grain N, N harvest index (NHI), N recovery index (NRI), mineral used N (MUN), biomass N use efficiency (NUE bmas), and

grain N use efficiency (NUE grn) for spring wheat near Sidney, MT, 2009-2012.

Treatment	Biomass	Grain	$PreNO_3$	$PostNO_3$	--Biomass N--		----Grain N----		NHI	NRI	MUN	NUE bmas	NUE grn
	------------------ kg ha^{-1} ----------------- g kg^{-1}					kg ha^{-1}	g kg^{-1}	kg ha^{-1}			kg N ha^{-1}	----kg kg^{-1} N----	
Rotation													
Continuous wheat	5395 b†	2234 b	59 a	42 a	17.8 a	94	26.9 a	60	0.65	0.7 b	74 a	147 b	60 b
Wheat-pea	5998 a	2510	47	29	17.0	100	25.	64	0.6	1.1	56 b	250	105

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		a	ab	b	ab		5 b		5	a		a	a
Wheat-barley-pea	5986 a	2488 a	37 b	27 b	16.0 b	95	24.4 b	61	0.65	1.0 a	53 b	228 a	97 a
Wheat-barley-corn-pea	5715 ab	2406 a	47 ab	29 b	16.9 ab	95	25.4 b	61	0.66	1.1 a	52 b	202 ab	85 ab
Management													
Conventional	6116 a	2611 a	47	32	16.5 b	98	25.2 b	65 a	0.68 a	1.0	58	247	104 a
Ecological	5431 b	2208 b	48	32	17.4 a	94	25.9 a	58 b	0.62 b	0.9	59	166	70 b
Tillage													
Tilled	5837	2394	53	33	17.5	100	26.3 a	63	0.64	1.0	60	245	101
No-till	5711	2426	42	31	16.4	92	24.9 b	60	0.67	1.0	57	168	73
Year													
2009	5833 b	2703 a	65 a	32 b	19.1 a	111 a	28.9 a	78 a	0.71 a	1.2 a	55 b	181 ab	87 a
2010	7394 a	2630 a	55 a	17 c	14.0 c	103 a	22.6 d	59 b	0.59 b	0.7 c	81 a	141 b	48 b
2011	4628 d	2199 b	29 b	35 ab	17.0 b	79 c	24.1 c	53 c	0.68 a	0.9 b	54 b	141 b	66 ab
2012	5240 c	2107 b	40 b	44 a	17.6 b	90 b	26.6 b	56 bc	0.62 b	1.2 a	44 b	363 a	146 a
Significance													
Rotation (R)	***	***	**	***	**	ns	***	ns	ns	***	**	*	*
Management (M)	***	***	ns	ns	**	ns	*	***	***	ns	ns	ns	*
Tillage (T)	ns‡	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
Year (Y)	***	***	***	***	***	***	***	***	***	***	***	**	***
R × M	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
R × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
R × Y	***	ns	***	*	ns	**	**	*	ns	*	*	ns	ns
M × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
M × Y	***	***	ns	ns	***	**	***	*	ns	ns	ns	ns	ns
T × Y	***	*	**	ns	**	***	**	*	ns	***	*	*	*
R × M × T	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
R × M × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
R × T × Y	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
M × T × Y	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
R × M × T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† Means followed by different lowercase letter within a column are significantly different at $P \leq 0.05$.

‡ Not significant.

Soil preplant nitrate N, 0-60 cm depth

Soil post-harvest residual nitrate N, 0-60 cm depth

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N harvest index, grain N / aboveground biomass N

N recovery index, grain N / fertilizer N + preplant nitrate, 0-60 cm depth

Mineral used N, total available N – fall soil nitrate, 0-60 cm depth

Biomass N use efficiency, biomass yield / NU, 0-60 cm depth

Grain N use efficiency, grain yield / NU; 0-60 cm depth

Table 4. Interaction between rotation and year for biomass, post-harvest residual soil nitrate N (PostNO_3), biomass N, grain N, N recovery index (NRI), and mineral used N (MUN) for spring wheat near Sidney, MT, 2009-2012.

Rotation	2009	2010	2011	2012
		Aboveground biomass, kg ha^{-1}		
Continuous wheat	6045	6540 b[†]	4413	4583
Wheat-pea	5480	7953 a	5025	5532
Wheat-barley-pea	6157	7729 a	4704	5356
Wheat-barley-corn-pea	5649	7354 ab	4369	5489
		PostNO_3, 0-60 cm depth, kg ha^{-1}		
Continuous wheat	52 a	16	42	60 a
Wheat-pea	27 b	16	34	41 ab
Wheat-barley-pea	24 b	21	31	32 b
Wheat-barley-corn-pea	24 b	16	35	42 ab
		Aboveground biomass N, kg N ha^{-1}		
Continuous wheat	121	91 b	82	82
Wheat-pea	104	115 a	84	95
Wheat-barley-pea	108	102 ab	80	91
Wheat-barley-corn-pea	110	103 ab	72	94
		Grain N, g N kg^{-1}		

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Continuous wheat	32 a	23	25	28
Wheat-pea	28 b	24	24	26
Wheat-barley-pea	26 b	22	24	25
Wheat-barley-corn-pea	29 ab	22	23	28
		Grain N, kg N ha^{-1}		
Continuous wheat	80	58 ab	52	49 b
Wheat-pea	78	65 a	57	56 ab
Wheat-barley-pea	74	57 ab	55	57 ab
Wheat-barley-corn-pea	80	54 b	49	61 a
		NRI		
Continuous wheat	0.6 b	0.6	0.8	0.8 b
Wheat-pea	1.4 a	0.6	1.0	1.5 a
Wheat-barley-pea	1.3 a	0.7	0.9	1.3 ab
Wheat-barley-corn-pea	1.3 a	0.8	0.9	1.1 ab
		MUN, kg N ha^{-1}		
Continuous wheat	94 a	95	65	42
Wheat-pea	39 b	94	51	40
Wheat-barley-pea	41 b	71	54	48
Wheat-barley-corn-pea	45 b	65	48	50

† Means followed by different lower case letters within rotations and years for a given parameter are significantly different at $P \leq 0.05$.

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Table 5. Interaction between management system and year for biomass, biomass N, and grain N for spring wheat near Sidney, MT, 2009-2012.

Management	2009	2010	2011	2012
		Aboveground biomass, kg N ha^{-1}		
Conventional	5565	7997 a[†]	4781	6123 a
Ecological	6101	6792 b	4475	4357 b
		Aboveground biomass N, g N kg^{-1}		
Conventional	20	13 b	18	16 b
Ecological	19	15 a	16	19 a
		Aboveground biomass N, kg N ha^{-1}		
Conventional	107	102	85 a	97 a
Ecological	114	104	73 b	84 b
		Grain N, g N kg^{-1}		
Conventional	29	21 b	26 a	25 b
Ecological	29	24 a	23 b	28 a
		Grain N, kg N ha^{-1}		
Conventional	79	62	60 a	60 a
Ecological	77	55	46 b	52 b

[†] Means followed by different lower case letters within management and years for a given parameter are significantly different at $P \leq 0.05$.

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Table 6. Interaction between tillage system and year for biomass, biomass N, grain N, N recovery index (NRI), mineral used N (MUN), and N use efficiency (NUE) for biomass and grain, for spring wheat near Sidney, MT, 2009-2012.

Tillage	2009	2010	2011	2012
		Aboveground biomass, kg ha^{-1}		
Tilled	5602	7727 a†	4772	5246
No-till	6063	7061 b	4484	5234
		Aboveground biomass N, g N kg^{-1}		
Tilled	20 a	15 a	17	17
No-till	18 b	13 b	17	18
		Aboveground biomass N, kg N ha^{-1}		
Tilled	112	115 a	83	89
No-till	109	91 b	75	92
		Grain N, g N kg^{-1}		
Tilled	30	24 a	24	27
No-till	28	21 b	24	27
		Grain N, kg N ha^{-1}		
Tilled	77	63 a	54	56
No-till	79	54 b	53	56
		NRI		
Tilled	1.0 b	0.7	1.0	1.3
No-till	1.4 a	0.6	0.9	1.1
		MUN, kg N ha^{-1}		
Tilled	69 a	79	51	42

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No-till	41 b	84	57	48
		NUE for aboveground biomass, kg kg^{-1} N		
Tilled	138 b	184	183	474
No-till	225 a	98	99	253
		NUE for grain, kg kg^{-1} N		
Tilled	65 b	59	85	193
No-till	109 a	36	46	99

† Means followed by different lower case letter within tillage system and years for a given parameter are significantly different at $P \leq 0.05$.

Table 7. Interaction among management system, tillage system, and year for grain yield for spring wheat near Sidney, MT, 2009-2012.

	Grain yield	
	Tillage system	
Management	Tilled	No-till
	----------kg ha^{-1}----------	
	2009	
Conventional	2602	2907
Ecological	2559	2742
	2010	
Conventional	3057 a†	2920 a
Ecological	2258 b	2285 b
	2011	

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Conventional	2285 ab	2414 a
Ecological	2157 ab	1938 b
	2012	
Conventional	2433 a	2273 ab
Ecological	1798 c	1924 bc

† Means followed by different lower case letters within rows and columns for a given year are significantly different at $P \leq 0.05$.

Table 8. Interaction among rotation, tillage system, and year for pre-plant soil nitrate N ($PreNO_3$) for spring wheat near Sidney, MT, 2009-2012.

	$PreNO_3$, 0-60 cm depth	
	Tillage	
Rotation	Tilled	No-till
	----------kg N ha^{-1}----------	
	2009	
Continuous wheat	157 a†	77 b
Wheat-pea	62 b	41 b
Wheat-barley-pea	49 b	30 b
Wheat-barley-corn-pea	58 b	47 b
	2010	
Continuous wheat	56	64
Wheat-pea	77	57
Wheat-barley-pea	48	37

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Wheat-barley-corn-pea	57	45
	2011	
Continuous wheat	20	19
Wheat-pea	30	31
Wheat-barley-pea	28	31
Wheat-barley-corn-pea	40	36
	2012	
Continuous wheat	37	40
Wheat-pea	45	30
Wheat-barley-pea	38	36
Wheat-barley-corn-pea	44	50

† Means followed by different lower case letters within rows and columns for a given parameter are significantly different at $P \leq 0.05$.

Table 9. Interaction among rotation, tillage system, and management system for biomass N concentration for spring wheat near Sidney, MT, 2009-2012.

	Biomass N	
	Tillage system	
Rotation	Tilled	No-till
	-------g N kg^{-1}-------	
	Conventional management	
Continuous wheat	17.1 abc†	17.3 abc
Wheat-pea	18.0 ab	15.4 bc

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Wheat-barley-pea	15.7 bc	15.0 c
Wheat-barley-corn-pea	17.8 abc	15.7 bc
	Ecological management	
Continuous wheat	19.4 a	17.3 abc
Wheat-pea	18.8 abc	16.9 abc
Wheat-barley-pea	17.0 abc	16.5 bc
Wheat-barley-corn-pea	17.4 abc	16.9 abc

† Means followed by different lower case letters are significantly different at $P \leq 0.05$.

Table 10. Interaction between rotation and management system for grain N concentration in spring wheat near Sidney, MT, 2009-2012.

	Management	
Rotation	Conventional	Ecological
	------Grain N, g kg^{-1}------	
Continuous wheat	27 a†	27 a
Wheat-pea	26 a	25 a
Wheat-barley-pea	23 b	26 a
Wheat-barley-corn-pea	25 a	25 a

† Means followed by different lower case letters are significantly different at $P \leq 0.05$.

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